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Multiscale Simulation Framework for Transient Wave Propagation in Viscoelastic Composites

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Wave propagation in architectured materials (e.g., phononic crystals and acoustic metamaterials) exhibit complex response patterns due to the interaction of macroscopic wave and microstructures, e.g., Bragg scattering and local resonance. Controlling these interactions offer tremendous opportunities in many engineering applications, such as cloaking, acoustic diode and vibration control. It has been recently recognized that favourable properties could be achieved by introducing material damping, which provides an additional degree of freedom in the design and tuning of the architectured materials.

The characterization of dynamic properties of these materials is largely focused on the steady-state unit cell band structure calculation. For transient analysis, direct numerical simulations are routinely used, which is computationally prohibitive due to the necessity to resolve the fine scale features of the microstructure. This motivates the development of multiscale methods that characterize the macroscopic behaviour of these materials accounting for the effect of microstructures in an efficient manner.

Gradient elasticity models were developed to describe the macroscopic phenomena accounting for the microstructural effects without the need to resolve them. The resulting equations of motion capture the dispersive behaviour induced by the material heterogeneity. It has been demonstrated that the capability of this method in predicting the dispersion relation of one-dimensional elastic layered composites up to the second pass band, provided that the length-scale parameters associated with the higher order gradients are appropriately calibrated. However, the identification of these parameters in multidimensional problems is an outstanding issue and this approach has so far been applied to elastic composites only. Computational homogenization models, on the other hand, pose nested and coupled initial-boundary value problems at the scale of the material microstructure and the scale of the structure. The problems at two disparate scales are evaluated numerically in a coupled fashion. The energetic consistency between the problems at the two scales are achieved through the Hill-Mandel condition. While these models have been successful in capturing wave dispersion in small-scale transient simulations, the computational cost is high for multi-dimensional structure-scale simulations. The currently available dispersive asymptotic homogenization models [1][2] are proposed for wave propagation in long wavelength regime. As the wavelength becomes shorter, the accuracy decreases, therefore, this model does not accurately capture the initiation of the first stop band. In addition, while the approaches mentioned above account for wave dispersion due to material heterogeneity in elastic composites, the effects of material damping were typically not considered [3][4].

In this effort, we present a spatial-temporal nonlocal homogenization model for wave propagation in periodic viscoelastic composites. Asymptotic expansion of up to the eighth order is employed to derive a system of governing equations with higher order spatial gradient terms. These governing equations describe the momentum balance of the corresponding asymptotic orders. The higher order spatial gradient terms are then transformed to fourth order spatial, fourth order temporal and mixed spatial-temporal gradient terms through manipulations that consider the momentum balance of lower asymptotic orders. Combining the fourth order governing equations at each asymptotic order into a single homogenized governing equation, the spatial-temporal nonlocal homogenization model that describes the macroscale wave propagation is consistently derived. All the model parameters are uniquely computed from the microscale equilibrium equations that are independent of the macroscale displacement, therefore, computed as an off-line process. The proposed model is formally similar to the gradient elasticity models. It is unique in that it applies to wave propagation in two-dimensional viscoelastic composites and that all length parameters are derived, rather than calibrated.

Through dispersion analysis of the spatial-temporal nonlocal homogenization model, physical and non-physical wavenumber solutions are identified. A reduced order model is then derived based on the physical wavenumber solution. The resulting model is a second order PDE, therefore, can be numerically evaluated without high order boundary conditions which are otherwise required by the fourth order governing equation. The nonlocal character of the reduced order model is retained through the nonlocal effective stiffness that is derived from the original spatial-temporal nonlocal homogenization model.

The proposed model operates in the Laplace domain because of the simpler form of the constitutive relation of viscoelastic material. The numerical inverse Laplace Transform is employed to transform the response field into time domain based on finite samples of the Laplace variables. For each sampled Laplace variable, finite element method is employed to evaluate the microscale equilibrium and the model parameters are then computed as a pre-processing step. Dispersion analysis in the Laplace domain is performed to compute the nonlocal effective stiffness using complex algebra. A Hybrid Laplace Transform/Isogeometric Analysis (HLT/IGA) is developed to solve the macroscale momentum balance equation, which provides high convergence rate for high frequency wave propagation simulation. Since each sampled Laplace variable is independent from others, the numerical implementation is performed in a parallel environment, which significantly improves the computational efficiency.

Transient wave propagation in two-dimensional domain with periodic elastic and viscoelastic microstructures is investigated and the proposed models were verified against direct numerical simulations. It is shown that the proposed model the proposed model extends the applicability of the homogenization theory to shorter wavelength scenarios due to the incorporation of the high order corrections. This allows it to capture wave dispersion and attenuation due to material heterogeneities in addition to the material damping. Compared to the dispersion analysis based on unit cell band structure, the transient simulation capability of the proposed model enables the characterization of wave propagation in finite domain with presence of different boundary conditions.

The key contributions of our work are: (1) wave dispersion and attenuation in viscoelastic composites are accurately captured in the first pass band and stop band; (2) all the model parameters are computed directly from the microscale equilibrium as an off-line process. These properties demonstrate the potential of the proposed model to serve as an efficient tool for the transient simulation of architectured elastic and viscoelastic materials.

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